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Enhancing Sustainable Nutrient and Irrigation Management for Potatoes

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*Two aspects of nutrient and irrigation best management practices (BMP) in relation to sustainable agricultural production systems described in this paper are: (i) application of crop simulation model for decision support system; and (ii) real-time, automated measurement of soil-water content to aid in optimal irrigation scheduling aimed at minimizing leaching losses below the root zone. Water transport through the soil profile within and below the crop root zone plays an important role in determining the nutrient transport, uptake, and possibly leaching below the crop root zone. Minimizing leaching losses is important to avoid wastage of nutrients and decrease or prevent nutrient contamination of surficial groundwater. Capacitance probes were used in this study for real-time, automated measurement of soil water content at various depths in the soil, i.e., within and below the root zone. Depth-integrated soil-water contents were calculated for the rooting depth and below the rooting depth during potato (*Solanum tuberosum*) growing season, and evaluated against the irrigation setpoints to monitor: (i) adequate soil-water content within the root zone to avoid any negative affects of crop water stress; and (ii) optimal irrigation scheduling to avoid water leaching below the root zone. In team research, a potato crop simulation*

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model was improved by upgrading various model parameters. The upgraded potato simulation model (CSPotato) was integrated with a multi-year, multi-crop simulation model, CROPSYST VB. This enabled us to improve overall model capabilities for the assessment of N dynamics, prediction of plant growth, and yield in potato-based cropping systems. In the integrated model (CROPSYST VB – CSPotato), CROPSYST VB simulates the soil-water-plant-atmosphere system for a crop rotation, as well as the water and nitrogen budgets. When the crop in the rotation is potato, CSPotato simulates potato growth and development and plant C and N balances. We have demonstrated that this integrated model successfully predicted plant biomass accumulation, leaf area index, and tuber yield of potato under different nitrogen and irrigation management conditions.

KEYWORDS *best management practices, crop simulation models, full and refill point, irrigation scheduling, nitrate leaching, soil water monitoring*

INTRODUCTION

Within the context of agricultural production systems, the word "sustainable" refers to a practice that is economically and technically feasible while minimizing the negative impacts on the environment. The technological breakthroughs of the early 1900s, combined with increased mechanization and use of chemicals to control crop diseases, pests, and weeds, contributed to maximizing production and net return per unit land. Although this is significant progress, there could be some concerns with respect to its impact on the environment. The latter must be recognized and quantified, and strategies should be developed to mitigate the negative affects, if any. Therefore, the role of sustainable agricultural production is to integrate the environmental stewardship with the goal of farm profitability.

Agricultural research, traditionally, has made significant contributions to the commercial farming industry by release of new cultivars with increased yield, improved quality and marketable traits, and resistance to pests and diseases as well as abiotic stresses. The efficiencies of crop management, harvest, handling, and storage have improved considerably, which led to maximum net returns per unit input cost. There is a general perception, mostly with the non-agricultural sector, that intense agriculture has negative impacts on the environment. For example, poor management of irrigation and application of chemicals and fertilizer in some cases can contribute to excess leaching and, in turn, lead to contamination of groundwater in quantities in excess of drinking water quality standards. This is referred to as "non-point source pollution" of groundwater. Therefore, during the recent years, increased emphasize has been directed toward sustainable production practices to minimize negative impacts on the environment while maintaining economic sustainability of agricultural production systems. Research-based studies are crucial to develop management practices to mitigate the above problems. These improved crop management recommendations are collectively referred to as "best management practices" (BMP). It is important to underscore the fact that BMPs are aimed at mitigating the negative environmental impacts of agricultural production practices with minimum adverse impact on the economics of farming, i.e., the proposed BMPs must be technically and economically feasible, in addition to being capable of mitigating the environmental problems. In other words, a BMP that requires modifications in production practices with a substantial increase in cost of production, leading to a reduction in net returns, is likely to face resistance in adaption despite its effectiveness in mitigating the negative environmental impacts.

The research-based BMPs have to be validated by comparative evaluation of conventional practices and the proposed BMPs. Monitoring the crop growth and yield responses to different management practices as well as environmental effects under different production regions is important to maintain consistency and facilitate multiple evaluations carried out in a timely manner. Crop response is highly dependent on a number of factors, including the soil and climatic variabilities. Response evaluations cannot be conducted under each and every possible production condition and agroclimatic regions. Therefore, crop simulation models are useful tools to predict the response under different production systems. This is the most cost-effective technique to develop crop production decisions to avoid the risk of economic failures and/or negative environmental impacts. It is important to underscore the fact that these crop simulation models must be robust and well calibrated for varied production and agroclimatic conditions, and validated with a high degree of confidence to improve the accuracy of predictions.

In this paper, an example of automation in soil monitoring to assist scheduling irrigation and a crop simulation model as an aid for a decision support system are presented. Both of these examples are related to improving environmental sustainability, conserving water and other crop productions inputs, and increasing net returns. These contributions are the result of more than a decade of research by a team of scientists from the Agricultural Research Service (a research agency of the United State Department of Agriculture), several land grant universities, and various state and local research and outreach agencies. To maintain relevance of the research and develop high-impact deliverables, we worked closely with agricultural producers as well as agribusiness partners.

RESULTS AND DISCUSSION

Potato Growth Simulation Model

Model description and development

Potato is an important crop in many countries around the world. The total world production of potato is about 360 million metric tons (NPC 2006). China and Russia are the leading countries for potato production, with each contributing 20% of the total world production. The United States ranks fifth in the world, with about 5.3% of the total world potato production. The farm-gate value of the U.S. potato production is about 3 billion dollars (NPC 2006). The U.S. Pacific Northwest (US-PNW: Washington, Idaho, and Oregon States) supports a wide range of agricultural production systems with an annual farm-gate value of about 13 billion dollars. The value-added returns of these commodities and the economic opportunities of the related industries are of significant importance to this region. The farm-gate value of potato production (54% of the U.S. total production) in the PNW is about $1.5 billion.

The Columbia Basin region in southeastern Washington is an important potato-production area. The climatic and soil conditions in this region are well suited for production of high yields (in excess of 80 Mg ha^{-1}) of high processing quality potatoes. Potato production in this region occurs under irrigation systems, predominantly center pivot. Soils used for potato production are sandy, coarse, and with low organic matter, which are vulnerable to nitrogen (N) leaching if water and N are applied in excess. Surficial groundwater nitrate (NO_3-N) levels in the region have increased in recent years; thus, there is a need to develop improved N and irrigation management practices as well as a need to assess their impacts on the environment. Increased scrutiny of impact of agricultural-production practices on the environment can influence the economic sustainability. Research is continuing to develop BMPs for irrigated potato rotation systems in the US-PNW (Alva, Collins, & Boydston 2002; Alva et al. 2002a, 2002b, 2003, 2005; Redulla et al. 2002; Alva 2004a, 2004b, 2006). The discussion on the BMP development will not be covered in this paper. Parallel studies have also been in progress on the application of a crop-simulation model to predict the potato-plant growth and tuber production as well as fate and transport of nitrogen in the potato-production systems.

SIMPOTATO is a potato growth-simulation model developed by Hodges (1992) and Hodges, Johnson, & Johnson (1992) based on the standards of the IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project. This model used radiation-use efficiency (RUE) for prediction of yield potentials under different production conditions (Manrique et al. 1991). Several researchers have used RUE as a basis for simulation of crop growth (Charles-Edwards 1982; Sivakumar & Virmani 1984; Gosse et al. 1986; Muchow & Davis 1988; Kiniry et al. 1989). The SIMPOTATO model incorporates the genetic diversity in potato cultivars and impact of environmental factors on potato cultivars with considerable genetic diversity (Manrique, Hodges, & Johnson 1990). Our recent team research contributed to improvement of the SIMPOTATO model by incorporating updated crop coefficients. The upgraded potato model (CSPotato) has been calibrated using the available data from long-term field experiments in the US–PNW.

The CSPotato simulation model incorporates improvements for better simulation of crop growth and biomass accumulation based on transpiration-use efficiency. This approach is better suited for the Pacific Northwest growing conditions characterized by high vapor pressure deficit (VPD). This is an improvement in prediction of biomass accumulation as compared with that by RUE-based calculation, which was done in most other potato simulation models. The latter approach is acceptable for growing conditions with low VPD that exist in temperate climate, but is unsatisfactory for growing conditions with high VPD that exist in the Pacific Northwest.

CropSystVB is a Visual Basic new version of the CropSyst model (Stockle, Martin, & Campbell 1994; Stockle, Donatelli, & Nelson 2003). CropSyst has been widely used to evaluate crop production and management strategies worldwide and specifically in the US-PNW (Stockle, Donatelli, & Nelson 2003). The upgraded CSPotato model has been integrated with CropSystVB to enhance the application of CSPotato model to potato-rotation cropping systems (J. Marcos, C. Stockle, & A.K. Alva, unpublished). In the integrated model, CropSystVB provides the framework for weather, location, soil and crop inputs, and for daily and annual soil and crop outputs. CropSystVB includes a mechanistic approach of the soil-water-plant-atmosphere system. It simulates crop growth and development and soil water and N balances for a crop rotation of several years. In CropSystVB-CSPotato, when the crop in the rotation is potato, the phenology and growth of potato, as well as the plant N and carbon (C) balances are simulated by CSPotato model. The application of the integrated CropSystVB-CSPotato model for predicting plant growth and tuber production of a major potato cultivar was evaluated under different nitrogen and irrigation-management practices in the Columbia Basin production region in the Pacific Northwest (Alva et al. 2004 2009; Marcos et al. 2004). The simulated values by the above model were compared with the measured values in an experiment, as described below (Alva et al. 2010).

Model validation

The experiment was conducted in a Quincy fine sand (sand content >95%) in Benton County, WA. Potato cultivar ‘Ranger Russet’ was used in this study. This cultivar is grown on about 30% of the Washington state potato acreage (about 69,000 ha). The experiment included a factorial combination of: (i) two irrigation regimes—irrigation to replenish full evapotranspiration

(ET) or 70% of ET; (ii) four rates of pre-plant application of granular N source (Urea), either 0, 56, 112, or 168 kg N ha^{-1}; and (iii) three rates of in-season nitrogen delivered as fertigation by center pivot-irrigation system—either 112, 224, or 336 kg N ha^{-1}.

The pre-plant nitrogen rates were broadcast as urea during the land preparation prior to planting. The planting was done on March 17, 2004, in 86-cm spaced rows in 20-30-cm high raised beds. The planting density was 45,600 plants/ha. Seedlings emerged about four weeks after planting (April 19, 2004). The in-season nitrogen application began four weeks after the seedling emergence with the annual nitrogen rate applied in five split applications, each at two-week intervals. The different irrigation regime treatments began on May 18, 2004, and continued for the remainder of the growing season. The 70% ET irrigation treatment was attained by adjusting pivot speed to apply 70% of water that was applied for the full-ET treatment. Therefore, sprinkler package and water distribution uniformity remained similar across both irrigation treatments. Different pre-plant and in-season N rates resulted in total N rates in the range of 112 to 504 kg ha^{-1}. During the growing season, plants were sampled from selected treatments at two-week intervals, cleaned, and dry-matter weights of leaves, stem, and tubers were measured. The leaf area index was also measured. The measured values were compared with those predicted by the simulation model to evaluate the accuracy of prediction (Figure 1). Overall, the model prediction compared favorably with the measured values. Therefore, the integrated CropSystVB- CSPotato model is a valuable tool to predict the crop growth and tuber production under different growing conditions.

Real-Time Monitoring of Soil Water Content in the Soil as a Basis for Scheduling Irrigation

Description of capacitance probes

In some intensive crop-production regions, there is a risk of leaching soil-applied soluble nutrients and/or pesticides. The management practices, i.e., forms, method, and frequency of application, influence the magnitude of this problem. Water is needed to carry these nutrients and/or chemicals through the soil profile. Therefore, rainfall and irrigation contribute to leaching losses. The presence of soluble nutrients and/or chemicals in the soil in amounts exceeding what can be utilized by the plants and excess water make the right combination for leaching of water carrying the nutrients and/or chemicals through the soil profile. When the water front is leached past the depth of root zone, there is a tendency for this water to continue leaching down the soil profile and eventually enter the surficial aquifer, thus, becoming the source of "non-point pollution" of surficial aquifer. Management practices that mitigate the leaching losses, yet maintain optimal

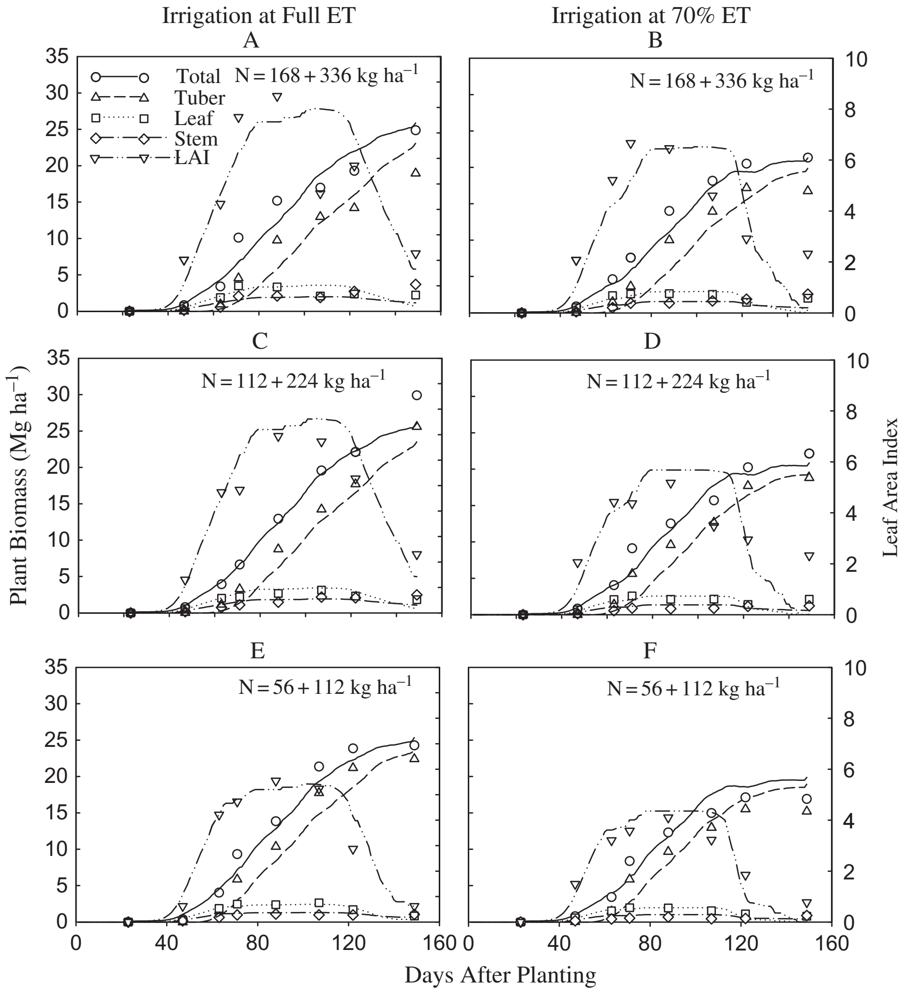

FIGURE 1 Biomass production in different parts of potato plants and leaf area index under different irrigation regimes and nitrogen management in a Quincy fine sand in the U.S. Pacific Northwest. The data points are measured values, while the lines for each response parameter represent values predicted by CropSystVB-CSPotato model.

availability of water and nutrients to the plants to support maximum crop production and net return are called "best management practices" (BMP). For a given BMP to effectively mitigate leaching losses of nutrients or chemicals, improvements in both water and nutrient application must be addressed.

In high-rainfall regions, minimizing nutrient leaching can be accomplished by managing application of nutrients to avoid the presence of nutrients in the soil in amounts exceeding that which can be utilized by the crop at any given time. This can be accomplished by increasing the frequency of application to lower the rate of application at any single application event. Alternatively, the nutrient can be applied in slow-release or controlled-release formulation. These modified fertilizer formulations facilitate extended period of nutrient release at low quantities to match the nutrient requirement by the crop across a prolonged period of time.

Frequency of fertilizer application can be increased conveniently by fertigation at a minimum increase in cost of application. However, this can be accomplished only if timing of each fertilizer application matches the timing of irrigation. In high rainfall production regions, particularly during the growing season when fertilizer delivery is important, fertigation may not be practical because irrigation as a part of fertigation can contribute to increased leaching losses if the soil had adequate stored moisture from rainfall.

In arid, low-rainfall regions, however, improved irrigation management is the key to minimize nutrient leaching losses. In center-pivot irrigation, uniformity of water application is an important factor that can influence the leaching losses. Monitoring soil-water content in the soil profile (within and below the root zone) is important to determine the water deficit within the root zone and adjust application of irrigation to replenish the deficit. Furthermore, continuous monitoring of soil below the root zone is used to guide irrigation to avoid water application in excess of crop requirement that can contribute to leaching of soluble nutrients and chemicals, resulting in negative effects on the environmental quality. Indeed, sustainable irrigation practice can be defined as irrigation management to overcome the potential effects of soil-water deficit to achieve maximum crop yields and quality to support higher profitability in a given production condition while minimizing leaching losses that can contribute to potential negative environmental effects.

The above objective can be achieved by incorporating advanced technologies for automated, real-time, soil-water monitoring at various depths in the soil profile within and below the depth of the root zone. Although there are a number of different sensors for measuring soil-water content, the adoption of a given sensor depends on the following factors: (i) one that has a large zone of influence to represent the soil-water content of the soil in a large area; (ii) a sensor that works well on most major soil types without the need for extensive calibration for each soil type; (iii) a sensor that can minimize the effects of changes in temperature, salinity levels, and moisture content across a reasonable range of the sensitivity of the sensor; (iv) the sensor reading should be minimally impacted by voltage fluctuation across a wide range; (v) a sensor that can last several years with minimal maintenance, yet provide accurate and repeatable measurements; and (vi) user-friendliness: ease of installation, maintenance, data access, interpretation, and guidelines for scheduling irrigation. In addition, rigorous testing of the sensor by independent research across multiple years and different soil and climatic conditions provides assurance to the creditability of the device and to its application to varied conditions. In the context of sustainability, however, it is important to understand the fact that adoption rate of any new technology is largely dependent on the demonstration of merit of the new technology. The merit can be judged both by the increased net returns over and above the cost of investment for that technology (both materials plus the cost of maintenance and operations), and environmental benefits, i.e., to overcome the degradation of water quality. The economics of the latter is somewhat difficult to judge because of complication of estimating the cost of the remediation of water-quality impacts.

Capacitance probes measure dielectric constant of soil-water-air complex. The dielectric constant of water is 80, soil is <10, and air is 1. Therefore, a slight change in water content in the soil will strongly influence the dielectric constant of the moist soil, which represents the soil-water-air continuum. Recent advances in microelectronics have facilitated continued measurement of dielectric constant in moist soil. This, in turn, provides an automated, reliable, and non-destructive technique for real-time measurement of the soil-water content. A set of multiple capacitance probes lowered into a polyvinyl chloride (PVC) access tube installed with minimum soil disturbance, thus provides a tool for real-time, continued measurement of soil-water content at various depths in the soil profile (Figure 2). The depth of measurement is based on the depth of root zone of the crop in question. It is highly recommended to have the capacitance probes at 2 to 3 depths within the root zone and at least 2 depths below the root zone. Monitoring the latter provides a basis to evaluate the potential leaching of water below the root zone.

Soil water monitoring

Continued real-time soil-water measurements made at various depths in the soil profile provide the following useful information (Figure 3): (i) changes in soil-water content at various depths following each irrigation or precipitation; (ii) free drainage of water and/or soil-water extraction pattern by the plant roots at various depths; (iii) estimation of depth of root zone and soil depth with maximum root activity; (iv) hourly or daily estimation of crop evapotranspiration; (v) estimation of soil-water-mass balance and amount of water leaching below the root zone; (vi) changes in integrated soil-water content in the root zone as an indicator of soil-water-extraction pattern by the plant roots and onset of soil-water stress; and (vii) development of irrigation set points to facilitate irrigation-management decisions.

Improved irrigation scheduling using real-time soil-water monitoring

Water management in the agricultural context has two important objectives: (i) to supply adequate water to the plants when and where needed while

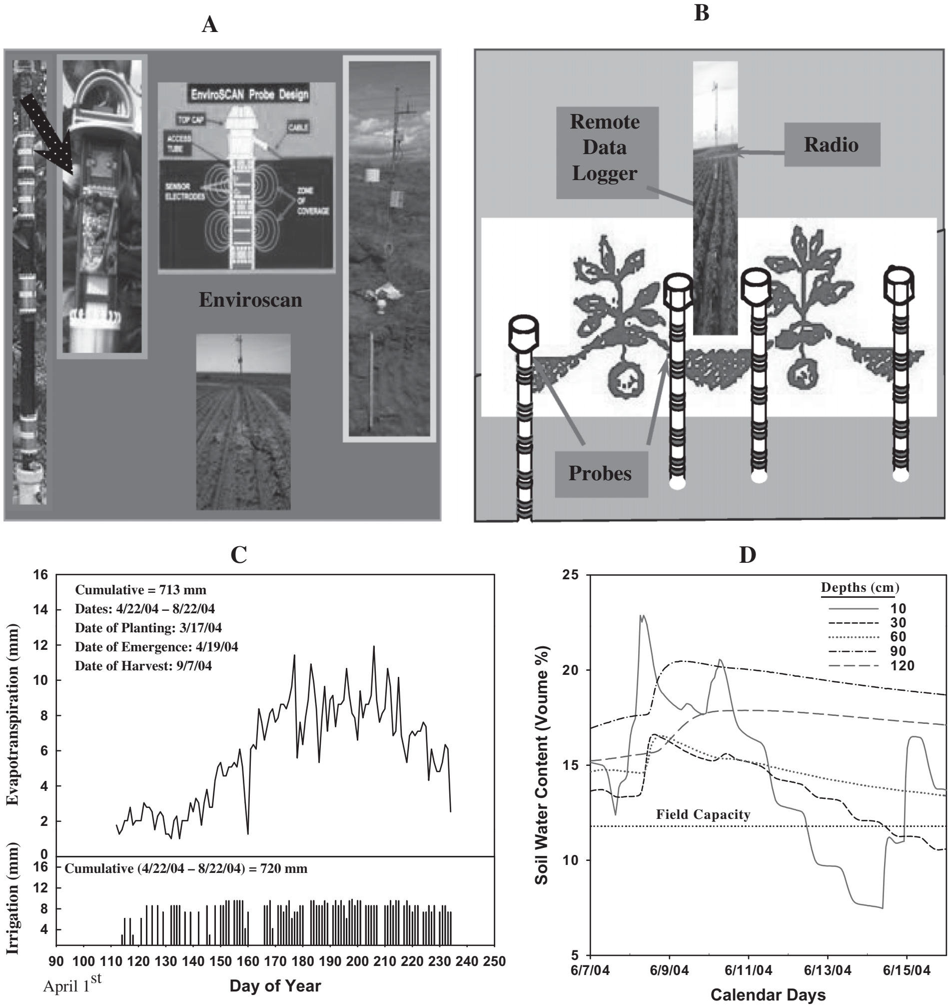

FIGURE 2 Enviroscan capacitance probe for real-time monitoring of soil water content at various depths in the soil (A). Layout of the soil water probes in a potato field showing the location and depth of probes in an access tube, and antenna for data transmission from the probes into a remote computer (B). Evapotranspiration (ET) and amount of irrigation during potato growing season in the U.S. Pacific Northwest, which has a dry climate with total dependence on irrigation to satisfy ET demand for crop production (C). Enviroscan probe data showing a sample of soil water content data over a nine-day period (D). The 10 cm depth data shows changes soon after irrigation with rapid drainage and subsequent changes in soil water content reflective of depletion in soil water content due to crop uptake (daytime) and no depletion (nighttime). This trend clearly shows a stair-step effect in soil water content changes.

minimizing the negative effects of water deficit on plant growth and production; and (ii) to avoid application of excess water that can leach below the root zone, carrying with it soluble nutrients and other agricultural chemicals

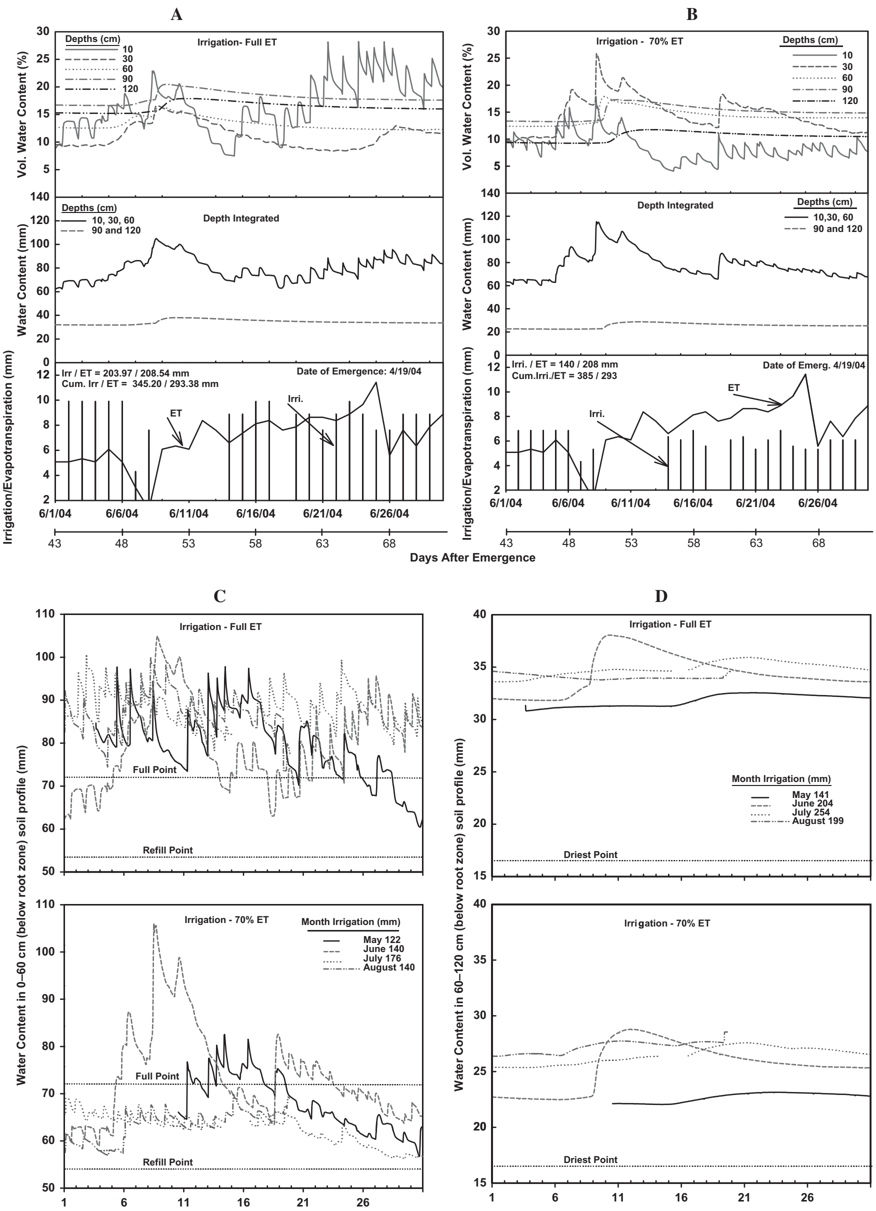

FIGURE 3 Sample of Enviroscan capacitance probe data for the month of June 2004 (peak potato growing period) for full ET (A) and 70% ET (B) irrigation treatments. The figures show the volumetric soil water content at various depths and depth-integrated soil water content for 0–60 cm (potato plant root zone) and 60–120 cm depth (below the root zone). The figure also shows the daily ET and irrigation events for June 2004. Figures C and D show depth-integrated soil water content for the 0–60 cm depth soil (potato root zone) for each month (May through August 2004) for two irrigation regime treatments (C) and similar data for the 60–120 cm depth (below the root zone) soil (D). Extracted from Alva (2008).

that can contribute to groundwater contamination. The adequate amount of water under most situations that can satisfy the evaporation (E) loss of water from the soil and the water loss from the plants is called transpiration (T). The two components combined constitute evapotranspiration (ET). As shown in Figure 2, ET follows the plant-growth pattern with lower ET amounts at the beginning and toward the end of the growing period, with peak demand during the maximum growing period. In an ideal situation, using the plants as an indicator, the amount of irrigation should match the ET to avoid the negative effects of water deficit on plant growth and production. Likewise, irrigation to match the ET should minimize leaching losses because applied water simply satisfies the ET demand, thus leaving no excess water to leach below the root zone.

Optimal irrigation recommendations can be developed using soil-water monitoring. Research has shown a definite relationship between the soil-water content and the dielectric constant of the soil-air-water mixture. The capacitance method can be used to measure the dielectric constant of the soil-air-water mixture, thus it can be a basis to estimate the soil-water content in the soil (Bell, Dean, & Hodnett 1987; Platineanu & Starr 1997; Starr & Platineanu 1998). The dielectric constant of soils can be measured by capacitance. Therefore, with the measurement of dielectric constant, the soil-water content can be estimated at a given time within the zone of interest.

Sentek Pty Ltd. Australia developed a new system for monitoring soil-water content on a real-time basis using semi-permanent multi-sensor capacitance probes (Figure 2) (Buss 1993). This system is designed to monitor soil water at various depths in the soil down to 500 meters and to automatically record the data on a data logger or transfer the data to computer via radio telemetry. Data can be logged at any desired time frequency. The capacitance probes are placed in a plastic access tube to the desired depth for any given application (Figure 2). In agricultural areas, the depth of monitoring is dictated by the depth of rooting so that real-time soil-water monitoring can be done both within the root zone and the zone below the rooting depth. The former gives the estimate of available water for plant uptake, whereas the latter gives an estimate of amount of water, if any, leaching below the rooting depth at a given point in time. Research conducted through the 1990s has shown the application of this technique for soil-water balance calculations, estimation of crop ET, and real-time monitoring as a basis for improving precision in irrigation scheduling (Alva & Fares 1998, 1999; Fares & Alva 1999a, 1999b, 1999c, 2000a, 2000b; Fares et al. 1997, 2000, 2002; Fraisse & Alva 2002).

In this study, we used the capacitance probes for real-time monitoring of soil-water content in a potato field in a sandy soil. The effective rooting depth of potatoes is 60 cm. Therefore, the sensors were installed at 10, 30, 60, 90, and 120 cm depths adjacent to the potato plants (Figures 2 and 3). The last two depths gave an indication of soil-water content below the root zone, thus enabling us to examine leaching of water below the root zone. The experiment was conducted in a potato (Ranger Russet; planted on March 17, 2004) field in the US-PNW (Quincy fine sand; mixed, mesic, Xeric Torripsamments; 96% sand) under center-pivot irrigation. Two irrigation regimes (replenish full ET; or replenish 70% ET) were evaluated. Two Enviroscan probes (each with sensors at 10, 30, 60, 90, and 120 cm depths) were installed for each irrigation treatment. Differential irrigation treatments began after row closure of the plant canopy (May 18, 2004).

Cumulative ET for the growing season was 750 mm (Figure 2). Cumulative irrigation was 798 and 702 mm for the 100% and 70% ET treatments, respectively. Figure 3 illustrates the volumetric water contents at each of the five depths for the two irrigation-regime treatments for May through August 2004. Water content measured at 10 cm depth showed a characteristic response to water applications. The peak water content quickly declined soon after water application stopped. This is an indication of rapid drainage in this sandy soil. The soil-water content at 30 cm showed some changes across time, particularly during June through August.

The remaining depths showed negligible changes in soil-water content across the entire monitoring period. Depth-integrated soil-water-content data are shown for 0–60 cm (rooting depth) and 60–120 cm (below the rooting depth) depth increments (Figure 3). The fluctuations in the depth-integrated water content at 0–60 cm depth are quite expected, which reflects the changes in soil-water content in response to irrigations and due to plant uptake. Depth-integrated soil-water content for below the rooting depth is generally constant, thus it is an indication of very little water leaching occurring below the rooting depth for both irrigation regime treatments.

The Enviroscan probe monitoring soil-water data give a clear indication of the soil depth that represents maximum root activity for water uptake. Because potato is a shallow-rooted crop, root activity was minimal at the soil depth below 60 cm. Therefore, there was no depletion of soil water at the subsurface horizons. Likewise, it is interesting to note that there was very little leaching from the soil above, as evidenced from the lack in increase in soil-water content at depths below 60 cm.

The procedure described above represents an automated, reliable technique for real-time monitoring of soil-water content both within and below the root zone of potato plants. The application of this information to commercial agriculture is dependent on how this information can be used to schedule irrigation to satisfy the dual role of avoiding the effects of soil-water deficit and minimizing leaching of water below the root zone. This is accomplished by developing the following set points as a basis to schedule irrigation. These set points are dependent on: soil texture classification; allowable soil-water deficit for a given crop without significant growth reduction and/or yield losses; rooting depth of the crop in question; and crop growth stage. Irrigation set points provide the upper and lower limits of soil-water content in the root zone so that irrigation can be scheduled to avoid the negative effects of excess or deficit irrigations (Alva 2008).

Full point. This indicates the amount of water that can be held in the soil, within the rooting depth, against gravity, i.e., after the excess water is drained. This can be equivalent to field capacity (FC) of the soil. The FC of the soil used in this experiment (Quincy fine sand) is 12% (v/v). The rooting depth of potatoes is 60 cm. Thus, the full point = 600 mm × 0.12 = 72 mm (Figure 3).

Driest point. This represents the depletion of soil-water content within the rooting depth to a point at which water cannot be taken up by the plants. Depletion of soil-water content to this level results in wilting of the plants. This is equivalent to the wilting point of the soil (WP). The WP for this soil is 3% (v/v). Thus, for 60 cm rooting depth, the driest point = 600 mm × 0.03 = 18 mm (Figure 3).

Refill point. This represents the soil-water content within the rooting depth at which irrigation must be scheduled to avoid possible negative effects of mild water stress on plant growth and production. For potatoes, the available soil moisture can be depleted by one-third without causing significant negative effects on plant growth and/or tuber production. This means that soil-water content can deplete from 12% to 9% (v/v). Therefore, the refill point is 600 × 0.09 = 54 mm (Figure 3).

Given the above set points, irrigation should be scheduled when the soil-water content in the root zone depletes to 54 mm. The length of irrigation should be adjusted to ensure that soil-water content in the root zone does not exceed 72 mm. It is equally important to monitor the soil-water content below the root zone to ensure that irrigation events are properly done to minimize leaching of water below the root zone. Ideally, the depth-integrated, soil-water content below the root zone should remain steady throughout the growing season. This is an indication that no new water leached below the root zone during the growing season. The soil-water set points developed in this study are useful for optimal scheduling of irrigation aimed at maintaining adequate soil-water availability within the root zone and minimizing leaching of water below the root zone. Irrigation scheduling to replenish 100% ET maintained the soil-water content in the 60 cm depth root zone above the full point most of the time. Therefore, under the conditions of this experiment, irrigations to replenish full ET may contribute to water leaching below the root zone. The deficit irrigation treatment (replenish 70% of ET) maintained the soil-water content between the full point and the refill point.

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